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KINEMATICAL AND DYNAMICAL ANISOTROPY: IMPLICATION OF SEISMIC FRACTURE CHARACTERISATIONS

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ABSTRACT

In characterising subsurface fractures, a standard practice is to analyse azimuthal PP-wave data for systematic variations in travel-time, amplitudes and attenuation characteristics. A persistent question is "Do we really need S or PS wave data for fracture characterisations?" Even if we can argue for S or PS data, it has been noted that the measured directions and magnitudes of anisotropy from P and PS (and S) waves often differ. These differences, as has been discussed, may be due to dipping or multiple sets of fractures or arguably, due to complex stress-fracture-fluid systems. Another related argument in the hydrocarbon industry concerns the values/potentials of long-offset PP-wave data versus multi-component data. One school of thinking favours long-offset PP data, which may be used for (AVO) inversions of Vp and Vp/Vs ratio (for interpretation of lithology, fluids and fractures, etc). Another school of thinking is in favour of multi-component data as it certainly can provide direct and more reliable information about Vs than that derived from P-wave data. This argument will continue until those who favour multi-component seismology prove the true usefulness of multi-component data. If indeed P-waves could provide the same amount of information as S-waves in terms of lithology and fractures, there would be no interests in using S-waves as it requires 3-component recordings, and is thus more expensive! Therefore there is a need to address the long-standing problem: are P-waves sufficient to characterize fractured reservoirs or do we really need to acquire S or PS wave data?

Another important question that has recently risen is when anisotropy, e.g. fracture orientation and density, inferred from the kinematical and dynamic attributes should be the same or different. By kinematical attributes, we refer to travel-time and velocity-based measurements, and by dynamic attributes we refer to amplitudes and related attenuation measurements. A question argued in the recent workshop on Q during the EAGE meeting in Madrid is: should travel-time/velocity measurements reveal the same anisotropy as amplitude and attenuation measurements. Theoretically, as travel-times/velocity may have different sensitivities to fluids from amplitude/attenuation measurements, the kinematical and dynamical anisotropies do not have to be the same. If this is the case, it will have huge implications in seismic fracture-fluid characterisations.

In this study, we shall attempt address these two questions through a series of synthetic and theoretical studies, i.e. (a) PP vs. PS AVOs: are P-wave data enough to characterise subsurface fractures? (b) Kinematical vs. dynamic anisotropy: Do travel-time/velocity and amplitude/attenuation measure the same anisotropic subsurface physical quantities? We first systematically examine the azimuthal variations of PP and PS AVO attributes in fractured media. In addition to three conventional P-wave AVO attributes (intercept A, gradient B and curvature C), we introduce two new PS AVO attributes $\hat{A}$ and $\hat{B}$ (which control near and far offset response of PS-waves, respectively). Previous studies of these parameters in isotropic media have suggested that they and their cross-plots may be used as good fluid and lithology indicators. However, there is no equivalent study of these AVO attributes for anisotropic media, except the simple but approximate analytic Rüger's equation for PP-waves. Here we perform a systematic study of these AVO attributes in anisotropic media to examine their azimuthal dependence and we find that all these attributes (B and C for PP-waves; and $\hat{A}$ and $\hat{B}$ for PS-waves) vary approximately with $\cos(2\varphi)$ (ϕ is azimuth angle) for near offsets. However, for middle and far offsets, a significant additional $\cos(4\varphi)$ variation is seen. We then perform analyses of synthetic seismograms produced for a complex fracture system: two fractured layers with different orientations and dip angles, and we attempt to estimate the fracture orientation using both PP and

PS AVO analysis. We find that fitting azimuthal AVO data with the cos2ϕ function with and without the cos4ϕ term results in differences even for small offsets, and therefore care must be taken when using only the cos2ϕ results for interpretation. For depth-dependent fracture orientation, it is not apparent how to determine the fracture orientations of each layer from PP data alone. With PS wave data, we can either use converted wave splitting or build a 2x2 component matrix (from orthogonal survey lines) and then perform the 2x2 component rotation or layer stripping if required to estimate multiple split shear-waves. However, for P-waves, there is no alternative. Determination of fracture dip angles from P-wave AVO analysis remains to be solved. One way of estimating the dip angle is to analyse the offset from PS positive and negative offsets for all azimuths and to identify any asymmetry in the arrival times and amplitudes, which may then be related to the dip angle. The azimuthal variation of converted PS waves is more sensitive to fractures than PP reflections. Even at small angles of incidence, PS reflections show distinct AVO variations. Our studies show that for the same total fracture densities, a model containing a single set of fractures show the largest variations of azimuthal AVO.

To answer the second question, i.e. kinematical vs. dynamic anisotropy, we systematically study the seismic response of media with two sets of fractures, where the two fracture sets have a range of conjugate angles and are filled with different fluids (or one is open and the second one is partially sealed, for example). As expected, in general multiple fracture sets tend to weaken the azimuthal response, in particular for PP waves. When the two fracture sets are filled with the same fluids, the velocity variation and attenuation variation have the same kind of anisotropy, i.e. same symmetry classes. In this case, the symmetry axis obtained from velocity anisotropy and amplitude/attenuation anisotropy is the same [Figure 1]. The azimuthal AVO analysis results in a symmetry axis in the average direction of the two fracture sets weighted by the fracture density of each individual set (similar to the behaviour of the polarizations of fast split shear-waves as has been studied previously). However, when the two fracture sets are filled with different fluids, or when one fracture set is open and the secondary set is partially sealed, the symmetry classes from velocity anisotropy and attenuation anisotropy will be different [Figure 2], in another words, symmetry direction or (effective fracture orientations) inferred from travel-time/velocity will be different from those obtained through analysis of azimuthal AVO data. This can be partially explained by the different sensitivity of kinematical and dynamic attributes to fluids – we argue that amplitude/attenuation are more sensitive to fluids than travel-time/velocity measurements, implying that prediction of fluid flow properties from seismic data, such as fluid pressure, permeability, and saturation will require measurements of both travel-times and true amplitude data.

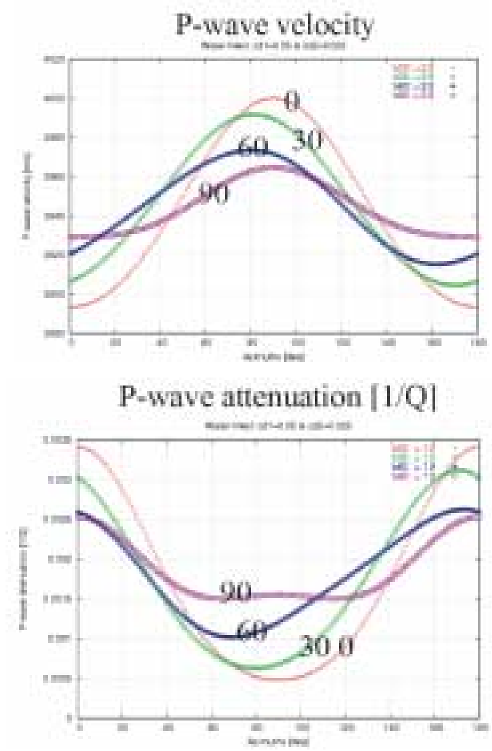

Figure 1. Variations of P wave velocity and attenuation with azimuths in media with two fracture sets filled with the same fluids (the fracture densities are 0.05 and 0.025).

In summary, PP and PS wave data are required to accurately characterize subsurface stress-fracture-fluid systems. Similarly, both kinematical data such as travel-times and velocity and dynamic data such as amplitudes and attenuation are required to characterise multi-fracture sets and their fluid properties. Further studies are certainly necessary to fully understand the seismic response of complex stress-fracture-fluid systems. In this study, we are beginning to address this important issue facing the seismic community. We argue that instead of reconciling the differences between various measurements, i.e. PP vs. PS (S) data and kinematical vs. dynamical data, we should realise that those different measurements provide different information about the complex subsurface stress-fracture-fluid systems. One of the main objectives of this work is to draw attention to the azimuthal variations of the PP and PS AVO attributes and their potential applications for characterizing fractured reservoirs, and to the kinematical and dynamical anisotropy of fractured media. We argue that the combined azimuthal analysis of the PP and PS travel-times and AVO attributes should aid interpretations in fracture characterization.

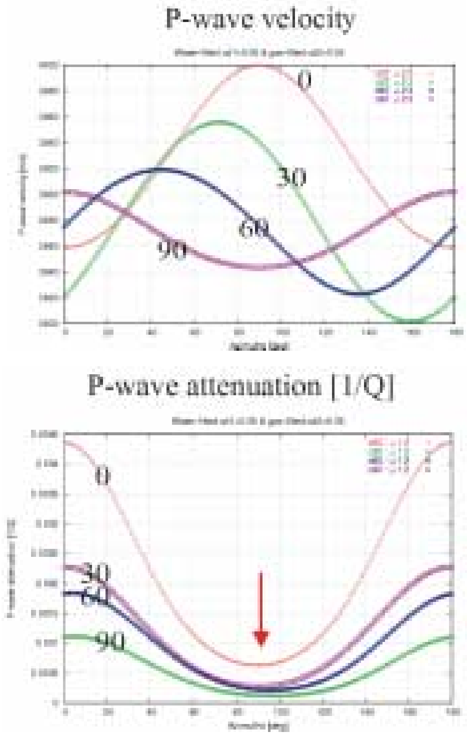

Figure 2. Variations of P wave velocity and attenuation with azimuths in media with two fracture sets filled with the water and gas, respectively (the fracture densities are 0.05 and 0.025).